

# Spectral Calibration of the EO-1 Advanced Land Imager

Jeffrey A. Mendenhall and Alexander C. Parker  
 Massachusetts Institute of Technology - Lincoln Laboratory  
 244 Wood Street, Lexington, MA 02420-9185  
 Tel. 781-981-0392, Fax 781-981-0969, e-mail: [mendenhall@ll.mit.edu](mailto:mendenhall@ll.mit.edu)

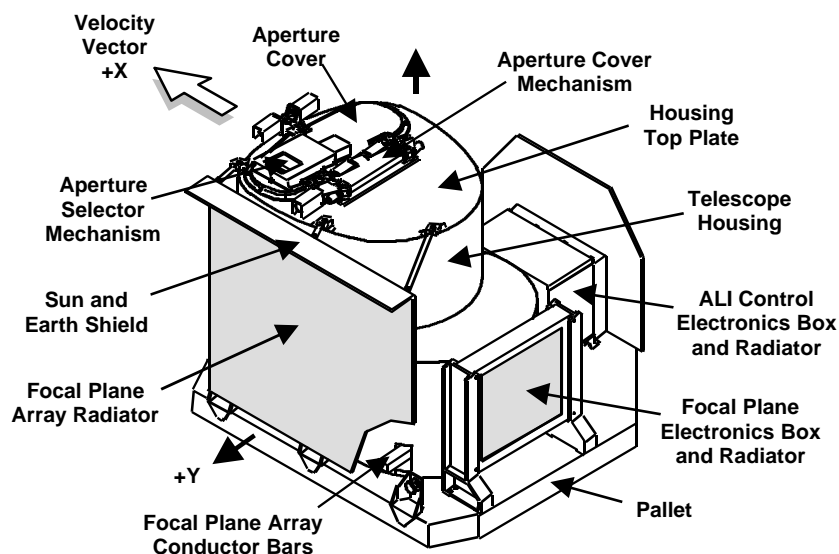
## ABSTRACT

The spectral response of the Earth Observing 1 Advanced Land Imager (ALI) has been characterized at Lincoln Laboratory as a fully assembled instrument in a thermal vacuum chamber at operational temperatures. The focal plane for this instrument is partially populated over a 3° cross-track segment with 9 multispectral bands having a 30-meter ground sample distance (GSD) and a single panchromatic band having a 10-meter GSD. These bands were selected to mimic the six Landsat-7 VNIR/SWIR bands with three additional bands covering 0.433-0.453, 0.845-0.890, and 1.20-1.30  $\mu\text{m}$ . The instrument system level response was characterized spectrally from 400-900 nm in 2 nm increments and from 900-2500 nm in 4 nm increments using a collimated monochromatic beam. Spectral artifacts introduced by the monochromator and the collimator were accounted for using spectrally calibrated silicon and lead-sulfide detectors which sampled the beam at each measurement interval. In this paper we describe the techniques employed during spectral calibration, present the measured in band and out of band spectral response for all VNIR bands, and compare the results to those obtained at the component level.

**Keywords:** calibration, EO-1, spectral, land imager

## 1. INTRODUCTION

The Advanced Land Imager is a technology verification instrument and will fly on Earth Observing 1 - the first Earth observing satellite in NASA's New Millennium program (Figure 1, Lencioni and Hearn 1998, Lencioni et al. 1999), Digenis et al. (1998)). The focal plane for this instrument contains 9 multispectral bands and a single panchromatic band (Table 1). These bands have been designed to mimic six Landsat (Lauer et al., 1997) spectral bands and provide three additional bands covering 0.433-0.453, 0.845-0.890, and 1.20-1.30  $\mu\text{m}$ . Additionally, the pushbroom optics of the ALI will provide



**Figure 1:** Earth Observing 1 Advanced Land Imager.

Band	Wavelength ( $\mu\text{m}$ )	Ground Sampling Distance (m)
Pan	0.48 – 0.69	10
MS-1'	0.433 – 0.453	30
MS-1	0.45 – 0.515	30
MS-2	0.525 – 0.605	30
MS-3	0.633 – 0.69	30
MS-4	0.775 – 0.805	30
MS-4'	0.845 – 0.89	30
MS-5'	1.2 – 1.3	30
MS-5	1.55 – 1.75	30
MS-7	2.08 – 2.35	30

**Table 1:** Spectral and spatial definitions for the ten EO-1 ALI bands.

substantially improved signal to noise ratios compared to the ETM+ (wiskbroom optics). The ALI is currently scheduled for launch on December 15, 1999 and will fly one minute behind Landsat-7 (launched April 15, 1999). In this configuration, both instruments will view identical scenes in order to verify the spatial, spectral, and radiometric performance of the ALI.

Ground calibration of the Advanced Land Imager occurred from September 1998 through January 1999 at the Massachusetts Institute of Technology/Lincoln Laboratory. Included in this characterization period was the spectral calibration of individual pixels of SCA 3 at the system level (Mendenhall et al. 1998). This paper provides a review of the techniques employed during spectral calibration and the first results from each VNIR band's in-band and out of band response. These results are contrasted to subsystem measurements obtained before the instrument was assembled. Subsystem measurements of the three SWIR bands are also presented.

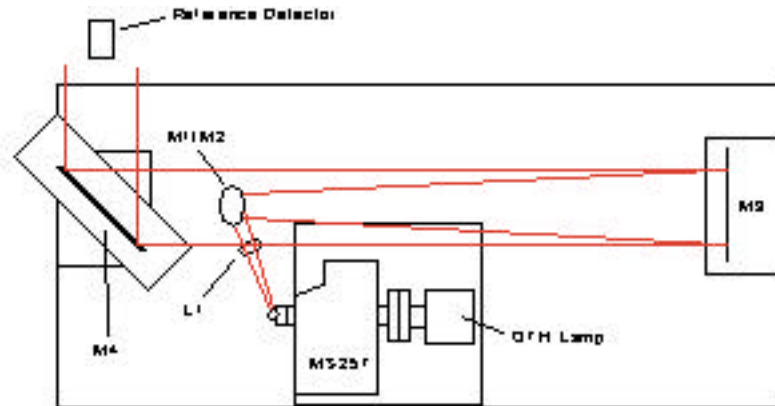
## 2. TECHNIQUE

Spectral calibration of the Advanced Land Imager was conducted on both the component and the system level. Subsystem level calibration was accomplished by evaluating the performance of each component individually by the manufacturer and then deriving the system level performance as the product of individual responses. Component level spectral characterizations include measurements of the ALI detector quantum efficiencies by Hughes Santa Barbara Research Center, filter transmissions by Barr Associates, and M1-4 and F1 mirror witness sample reflectivities by SSG Incorporated.

System level spectral calibration of the fully assembled flight instrument was performed at Lincoln Laboratory under vacuum and operating at expected flight temperatures. A spectral collimator was used to project a monochromatic beam into the vacuum tank via a quartz window. Data were collected from 400 nm to 2500 nm to map both in-band and out-of-band response for pixels in each of the nine multispectral and panchromatic bands.

### 2.1 Spectral Collimator

The collimator used during system level spectral characterization of the ALI may be divided into three sections: source, collimating optics, and beam monitor (Figure 2).



**Figure 2:** Collimator used during spectral calibration of the EO-1 Advanced Land Imager. The halogen lamp and monochromator are used as the source. L1 is a condensing lens, used to provide a 3" spot at the focus of the collimator. M1 and M2 are turning flats, M3 is a 17" diameter parabola used to collimate the beam, and M4 is a 20" diameter turning flat.

The source is composed of a quartz tungsten halogen lamp, monochromator, and integrating sphere. The halogen lamp provides a stable broadband source and is used to fill the f4 entrance cone of the monochromator. The spectral bandwidth passed through the system is defined by the blaze wavelengths of the four gratings and slit widths of the *Oriel MS257* monochromator. Upon exiting the monochromator, the beam was randomized into a uniform 0.5" diameter spot using a 2" diameter (id) *LabSphere Spectralon* (Leland and Arecchi, 1995) integrating sphere.

The primary component of the spectral collimating optics was a 17" diameter, 100" focal length off-axis parabola. This mirror was mounted such that its focus was at the distance of a condensing lens (L1) placed near the exit of the integrating sphere. The condensing lens was positioned to expand the output of the integrating sphere and provide a 3" diameter field for calibration. Collimated radiation reflected from the parabola was directed into the vacuum tank window using a large (20" diameter) flat mirror. A light tent was positioned around the spectral collimator and an intricate baffling scheme was adopted to prevent stray room light from contaminating the dim monochromatic output for this measurement.

The spectral collimator also contained two reference detectors, used to monitor the beam stability and flux throughout spectral calibration of the instrument; a silicon detector for VNIR measurements and a lead sulfide detector for SWIR measurements. Each detector was chopped and a lock-in amplifier was used to accurately subtract dark current drift and background radiation.

### 3. SYSTEM LEVEL CALIBRATION DATA COLLECTION

Spectral calibration data were collected in December, 1998 in a class 1,000 clean room at Lincoln Laboratory. This calibration was conducted with the ALI as a fully assembled instrument in a thermal vacuum chamber at operational temperatures.

A DELL 266 MHz PC (Windows 95 platform) controlled the monochromator scanning and beam sampling using a GPIB interface and LabVIEW control software. For very near infrared (VNIR) measurements (400-1000 nm) a spectral bandwidth and sampling interval of 2 nm was selected for spectral calibration. For short wave infrared (SWIR) measurements (1000-2500 nm) a spectral bandwidth and sampling interval of 4 nm was used.

Data collection consisted of iteratively sampling the beam with the reference detector and ALI. Initially, specific wavelength was selected by the monochromator. Next, a translation stage positioned a silicon or lead sulfide detector and chopper

between the beam and vacuum tank window. After sampling the beam, the detector was moved to an out-of-beam position. All bands of the ALI then sampled the monochromatic beam. Finally, a filter wheel acting as a shutter between the light source and monochromator blocked the incident beam to provide a dark reference for each spectral sample.

#### 4. ANALYSIS

Analysis of subsystem measurements was provided by each manufacture. Results from these measurements have been interpolated onto a 1nm spectral sampling interval. The overall system level performance was then calculated for each band as the product of subsystem measurements as a function of wavelength, normalized to unity at the peak response.

Analysis of the ALI system level spectral calibration data was conducted at Lincoln Laboratory and centered on the normalization of a given pixel's response (dn) to account for beam flux and vacuum tank window transmission artifacts as a function of wavelength ( $\lambda$ ). Initially, the ALI pixel response is offset corrected by subtracting dark scene values for each wavelength. A plot of spectral transmission versus wavelength is then generated for a given pixel by accessing data for a particular spectral calibration run and the wavelengths covered at that time. Artifacts induced by the vacuum tank window are then removed by dividing the pixels spectral response by the window's previously measured spectral transmission. Next, the varying flux of the incident beam as a function of wavelength are accounted for by dividing the pixel spectral response by the beam flux measured at each wavelength by the silicon or lead sulfide detectors. Finally, the spectral response of the reference detector itself is removed by multiplying the beam flux measurement by the detector's responsivity for the spectral range of interest. The above technique may be shown analytically using the following relation

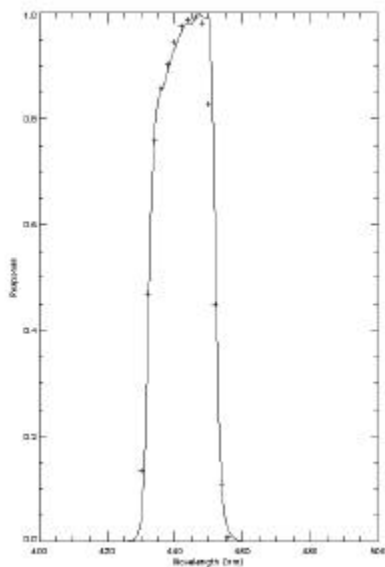
$$S_p(b, \mathbf{I}) = \frac{R_p(dn, \mathbf{I}) R_d(\mathbf{I})}{T_w(\mathbf{I}) F(\mathbf{I})}.$$

Here,  $S_p(b, \mathbf{I})$  is the derived spectral response for pixel  $P$  as a function of band  $b$  and wavelength  $\mathbf{I}$ ,  $R_p(dn, \mathbf{I})$  is the ALI focal plane response for pixel  $P$  as a function of wavelength,  $T_w(\mathbf{I})$  is the spectral transmission of the vacuum tank window,  $F(\mathbf{I})$  is the measured flux of the beam as function of wavelength, and  $R_d(\mathbf{I})$  is the spectral responsivity of the detector used to measure the beam.

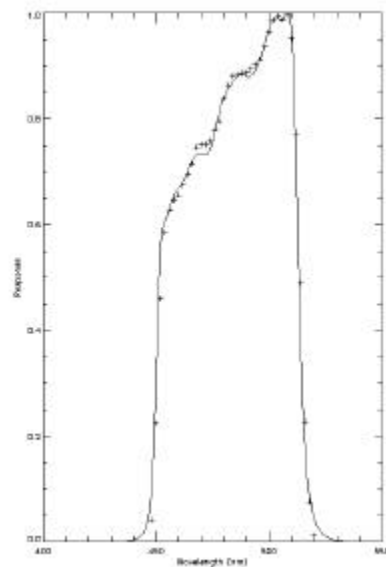
Once the above corrections are applied, the resulting spectral response function for a given pixel is normalized to unity at the peak response and compared to the theoretical spectral response of the ALI (generated from the subsystem measurements).

#### 5. RESULTS

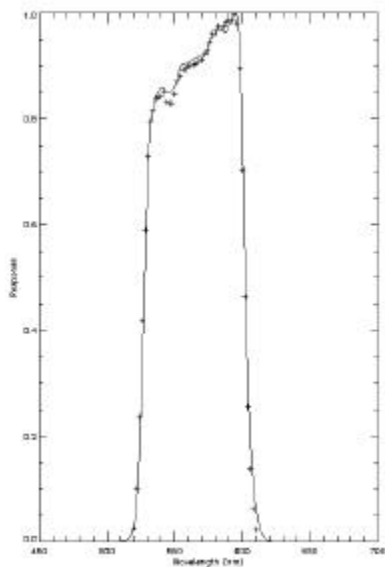
At this time we have generated system level spectral response functions for all ALI VNIR and panchromatic bands. Figures 3-9 compare the spectral response functions generated by using the above analysis and theoretical response functions generated using subsystem measurements. In all cases, the cut-on and cut-off wavelengths agree to within 1 nm of the subsystem level measurements. Additionally, subsystem measurements provide an upper limit of 1% for out of band responses for all bands. At this time, these responses have been confirmed to 2% using system level measurements. We also find excellent morphological agreement for all bands. The panchromatic band (Figure 9) in particular reveals good agreement between system and subsystem level measurements despite intricate variability across this band's spectral bandpass. Finally, Figures 10-12 depict the theoretical spectral response functions for the ALI's three SWIR bands. These responses have been generated using data collected at the subsystem level.



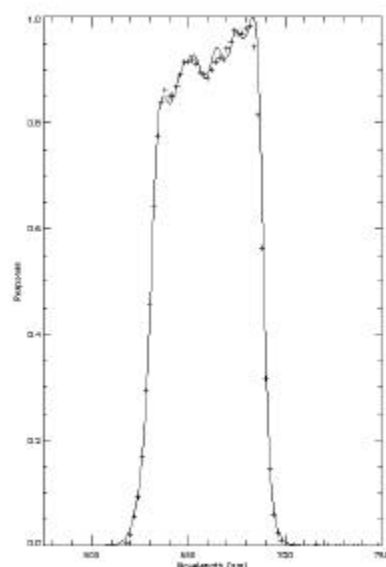
**Figure 3:** ALI spectral response function for band 1p. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem measurements.



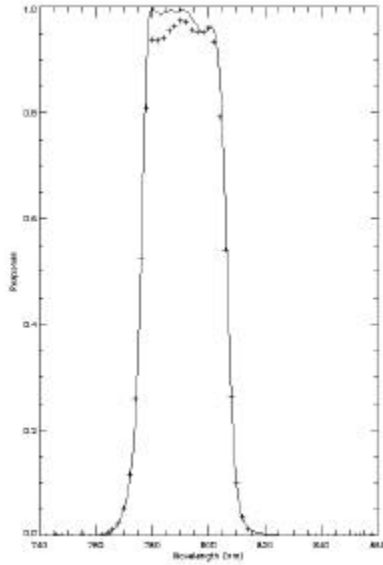
**Figure 4:** ALI spectral response function for band 1. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem level measurements.



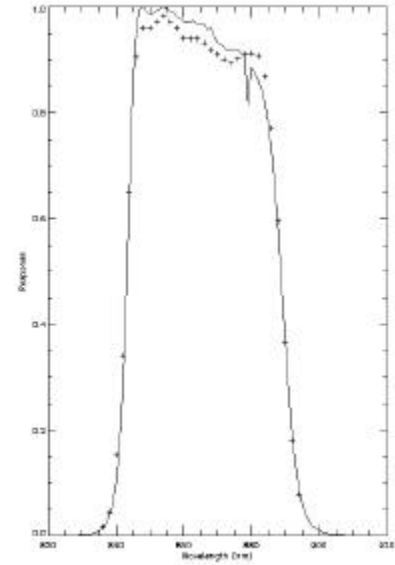
**Figure 5:** ALI spectral response function for band 2. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem measurements.



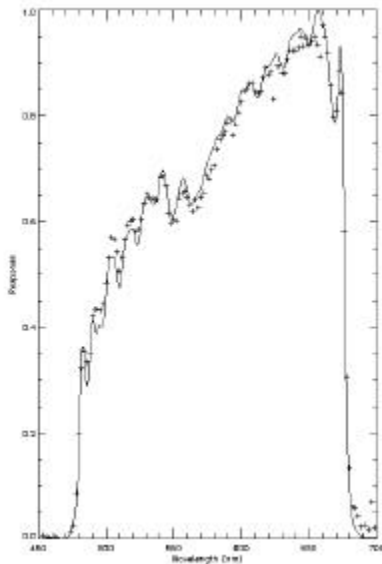
**Figure 6:** ALI spectral response function for band 3. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem level measurements.



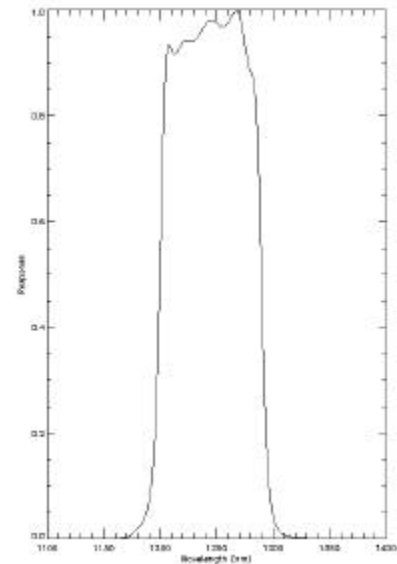
**Figure 7:** ALI spectral response function for band 4. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem measurements.



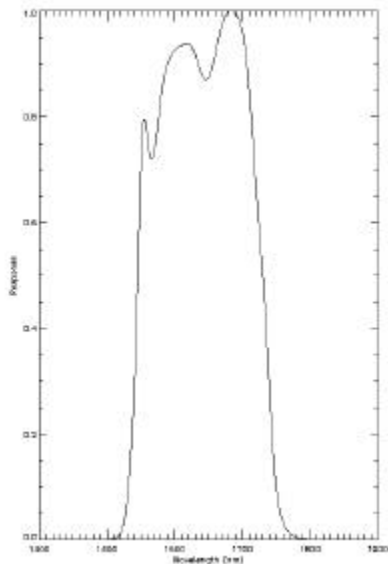
**Figure 8:** ALI spectral response function for band 4p. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem level measurements.



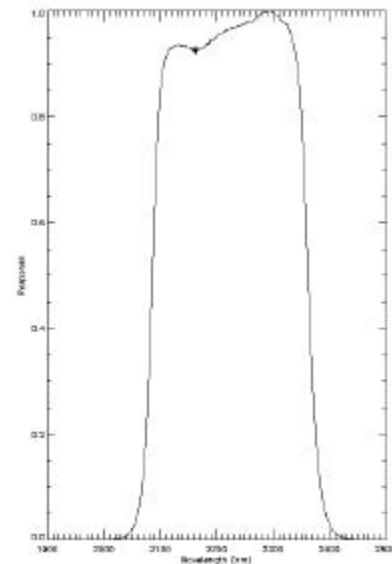
**Figure 9:** ALI spectral response function for panchromatic band. Crosses indicate system level measurements. The theoretical response curve was generated from subsystem level measurements.



**Figure 10:** Theoretical ALI spectral response function for band 5p generated from subsystem level measurements.



**Figure 11:** Theoretical ALI spectral response function for band 5 generated from subsystem level measurements.



**Figure 12:** Theoretical ALI spectral response function for band 7 generated from subsystem level measurements.

## 7. DISCUSSION

We find the system level ALI VNIR spectral response measurements are in excellent agreement with theoretical models generated from subsystem measurements. We find the spectral response of the ALI to be primarily dependent on the spectral response of the band defining filters lying directly above the focal plane. Detector quantum efficiencies also have a small effect on the spectral response of this instrument. This is particularly true for bands with larger bandpasses, such as the panchromatic band. For this band, the gradually increasing efficiency of the silicon material must be accounted for to accurately predict the spectral response of the ALI. Finally, mirror response has little effect on the spectral response of the instrument, providing a global diminution of ~5% which is not a factor when band responses are normalized to unity.

We have adopted the finer spectrally sampled subsystem measurements as the spectral response of the Advanced Land Imager for the VNIR and panchromatic bands. This response will be used to define the spectral bandpass for each band during the analysis of in-flight data. This response has also been adopted for calculating the in-band radiance of each pixel during radiometric calibration of the ALI. Finally, the spectral response of ALI bands 1, 2, 3, 4, and the panchromatic band presented in this paper closely match corresponding Landsat 7 ETM+ VNIR and panchromatic bands. This spectral consistency assists in assuring spectral continuity between these instruments when validating the ALI as a possible Landsat follow-on.

## 8. ACKNOWLEDGEMENTS

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Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force.

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